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Temperature Effects on Fatigue of Polymer Composites

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Introduction

Fiber-reinforced polymeric composites(FRPC) have been extended from aerospace, automotive, and military applications into civil engineering structures[1,2]. There is an urgent need to assess the safety and reliability of using polymeric composites in these applications. One particularly critical issue in regards to using polymeric composites in structural applications is their fatigue reliability in different environmental and loading conditions. Fatigue damages in polymeric composites for non-civil engineering applications have been extensively investigated. Studies of the effects of water and saltwater on fatigue behaviors of polymer composites have been reported. However, there is little quantitative research on the effects of civil engineering environments, namely, water, seawater, temperature, concrete pore solution, ultraviolet light, and loading on the fatigue of polymeric composites.

We have developed a fatigue model for predicting the fatigue life of fiber-reinforced polymeric composites, that incorporates applied maximum stress, stress amplitude, loading frequency, residual tensile modulus, and material constants as follows[3]:

$$\frac{dD}{dN} = (C_1 + \frac{C_2}{f}) \frac{(S_{max}^2(1-R))^m}{(1-D)^n} \quad (1)$$

$$\frac{1}{n+1} - \frac{(1-D)^{n+1}}{n+1} = (C_1 + \frac{C_2}{f})(S_{max}^2(1-R))^m N \quad (2)$$

$$\frac{1}{n+1} = (C_1 + \frac{C_2}{f})(S_{max}^2(1-R))^m N_f \quad (3)$$

where,

D is the state of damage defined as $D = 1 - E/E_0$, and E and E_0 are the residual and initial moduli, respectively,
C_1, C_2, m, and n are the material constants,
S_{max} is the maximum stress, or the normalized maximum stress to ultimate stress,
f is the fatigue loading frequency,
R is the ratio of minimum to maximum stress,
N is the number of loading cycles before failure, and
N_f is the number of loading cycles at failure.

The model has been verified with experimental fatigue data from a glass fiber/vinyl ester composite in various environments: air, fresh water, and saltwater at 30°C. This study investigates the effects of temperature on fatigue life of a vinyl ester/E-glass fiber composite submerged in seawater.

Experimental Procedure

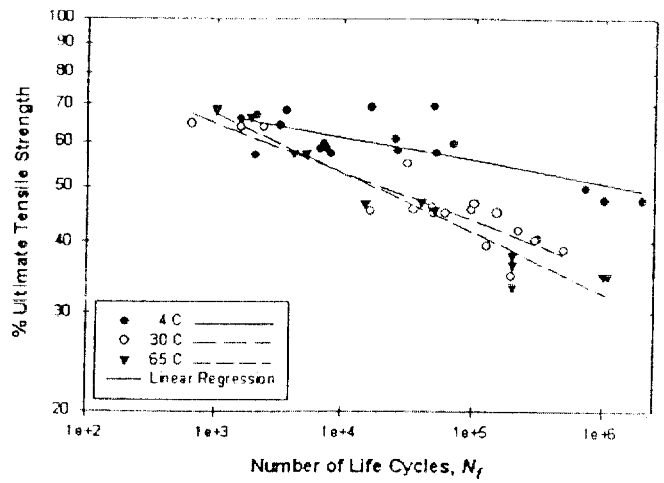
In this paper, we only briefly describe the experimental procedure to provide background information. For a complete description, readers may refer to [3]. The specimens used in these experiments are obtained from a vinyl ester/ E-glass fiber composite. The flat laminate composite is a cross-ply material with unidirectional roving and a random mat of continuous fibers in the off-axis. The specimens are cut into rectangular shapes, 200 *mm* long, 25 *mm* wide, and 3.2 *mm* thick. The edges of the specimens are then coated with epoxy to prevent the sorption of water into the composite from the edges.

Fatigue experiments are conducted in a tension-tension mode with a R value of 0.1. Maximum applied load ranges from 35% to 70% of ultimate tensile strength, and frequency is set at 10 Hz for studying temperature effect. All experiments are conducted at three temperatures (60°C, 30°C, and 4°C) on a servo-hydraulic fatigue test frame that has a tension-compression load capacity of 100 kN. The specimens used to simulate saltwater environments are attained by immersing in a 3.5% NaCl solution at 65°C for 451 hours to reach 95% of saturation. Before fatigue loading, the ultimate tensile strength, modulus, and Poisson's ratio are measured in dry air (45% relative humidity at 30°C) and in salt water environments.

Temperature Effects

Both the residual mechanical properties at specified loading cycles and the number of cycles at which the specimens fail are measured. The results show, for the material used in this study, that the fatigue life in these aqueous environments at 65°C is about the same as that at 30°C, but the fatigue life at 4°C is significantly longer than that at 30°C. Fig. 1 shows the experimental results and linear regressed S-N curves.

Fig. 1. S-N Cuves for Three Temperatures.



As shown in Fig. 1, the downward slope of the S-N curve, (i.e. $-1/2m$), goes further downward as the temperature increases. This clearly indicates that the value of m is temperature dependent, and that m value decreases as temperature increases. The continuing downward slope as temperature increases may expressed by the Arrhenius type equation:

$$slope = (-\frac{1}{2m}) = (-\frac{1}{2m_0})\exp(-\frac{Q}{RT})$$

where Q is the activation energy, R is the gas constant (8.134 joules-moles^{-1} K^{-1}), and T is temperature in K. Thus , the m value becomes:

$$m = m_0 \exp(\frac{Q}{RT}) \quad (4)$$

We can then plot the natural $log(m)$ vs. $1/T$ (Fig. 2) and obtain:

$$m = 0.018 \exp(\frac{1800}{T}) \quad (5)$$

This equation gives an active energy of $Q = 14.6\ k$ joules-moles^{-1} for the material used in this study.

The experimental data and the S-N curves in Fig. 1 also shows that the maximum stresses for all three temperatures at $N_f = 1000$ are approximately two thirds of respective ultimate strength. Also Eq. 3 can be rewritten as:

$$2m \log(S_{\max}) + \log N_f = \log C \quad (6)$$

where C represents a combined constant in Eq.3 *Thus*,

$$\log C = 2m \log(2/3) + 3 = 3 - 0.35m \quad (7)$$

Fig. 3 shows the temperature effect on the fatigue life with $R = 0.1$ and $Smax$ = 50% of ultimate strength. The data points are obtained from the S-N curves in Fig. 1 and plotted fatigue life curve is computed based on the m value form Eq. 5 and N_f from Eq. 6 and Eq. 7. Fig. 3 shows that the fatigue life of vinyl ester/E-glass fiber composite is reduced by two orders of magnitude as temperature increases from 4°C to 65°C. This result also indicates that polymer composites reinforced by glass fiber alone could not sustain the fatigue life the civil engineering infrastructure requires. Therefore, a hybrid reinforced with fatigue-resistant fiber such as carbon fibers would be needed to sustain needed fatigue life for civil engineering structures.

Fig. 2. Natural Log(m) vs 1/T.

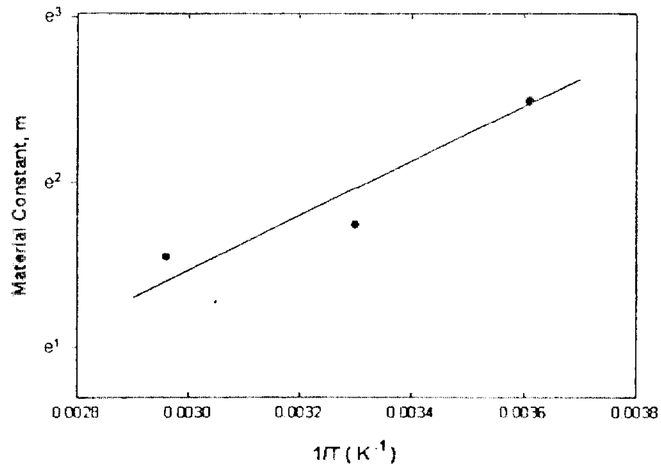
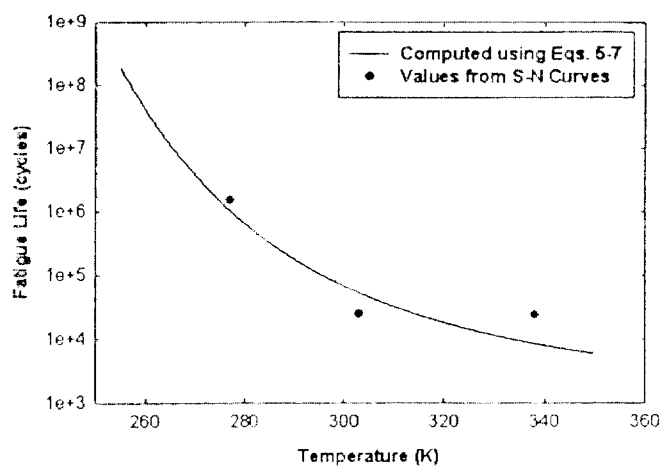


Fig. 3. Temperature Effect on Fatigue Life for Maximum Loading at 50% of Ultimate Strength and R=0.1.



Acknowledgment

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